JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 107, NO. A10, 1332, doi:10.1029/2002JA009381, 2002

The dayside reconnection X line

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Received 12 March 2002; revised 16 April 2002; accepted 24 May 2002; published 31 October 2002.

[1] The antiparallel reconnection hypothesis states that reconnection occurs at or near the locus along which magnetosheath and magnetospheric fields are antiparallel and the reconnecting component of the magnetic field is maximal. Recent observations have pointed toward significant reconnection rates in locales with much less than antiparallel field shear. We explore the alternative component reconnection hypothesis that reconnection occurs along a locus determined by integrating the local X line (XL) direction away from that region with the largest reconnecting field magnitude. We develop a description of the magnetospheric and magnetosheath magnetic fields at the magnetopause, compute the angle between the sheath and boundary layer fields, and the reconnecting component, everywhere on the magnetopause. We then integrate the XL across the magnetopause from a starting point or points where the reconnecting component is maximal. The resultant XL lies across the equatorial subsolar magnetopause for southerly *Bz*, as expected. For typical interplanetary magnetic field (IMF) conditions dominated by *By*, the XL tilts poleward and loops around the cusps into the high-latitude regions, consistent with throat-like cusp region flows. For northerly *Bz*, the XL bifurcates into high-latitude and low-latitude segments with subsolar reconnection disappearing only for mainly northward *Bz*. We argue that the component reconnection XL represents the mean location of quasi-steady reconnection on the magnetopause, subject to of course to nonuniformities and variations of the interplanetary magnetic field and plasma. We conclude that reconnection should have appreciable rates across the subsolar magnetopause for most IMF clock angles, with higher rates at high latitudes for northward *Bz*. *INDEX TERMS:* 2724 Magnetospheric Physics: Magnetopause, cusp, and boundary layers; 2728 Magnetospheric Physics: Magnetosheath; 2740 Magnetospheric Physics: Magnetospheric configuration and dynamics; 2731 Magnetospheric Physics: Magnetosphere—outer; *KEYWORDS:* magnetopause, reconnection, X line

Citation: Moore, T. E., M.-C. Fok, and M. O. Chandler, The dayside reconnection X line, *J. Geophys. Res.*, *107*(A10), 1332, doi:10.1029/2002JA009381, 2002.

1. Introduction

[2] Reconnection is usually described as a process through which magnetic field energy is converted into fluid flow energy. When highly stretched magnetic fields relax with the separation of a plasmoid via reconnection, this is obvious. However, when reconnection is a continuous process (apart from fluctuations around a mean rate), this is far less clear, as for example in the driving of the magnetosphere by relatively steady solar wind flow conditions at the dayside magnetopause. In such a case, reconnection may be described as a means of changing the magnetic topology such that strong coupling of mechanical energy occurs between two regions that would otherwise slip past each other with very little friction.

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0148-0227/02/2002JA009381$09.00

[3] In the simplest two-dimensional situations, magnetized regions of opposing polarity form a separating current sheet. The pinch effect ($\mathbf{J} \times \mathbf{B}$ force) tends to compress the current sheet into an unstable equilibrium that leads to one or more localized X lines (XLs), through which oppositely directed field lines reconnect and contract, releasing potential energy stored in the opposing magnetic fields, and using that energy to pump plasma along the current layer away from the site of reconnection. The solar wind and interplanetary magnetic field are continually incident upon the dayside magnetopause, giving rise to substantial transfer of plasma, energy, and momentum between the solar wind and the magnetically conjugate ionosphere, exciting the entire magnetosphere into circulation. Hence it is important to understand where and with what rate reconnection occurs at this boundary and how this depends on solar wind conditions. The goal of this paper is to contribute toward such an understanding.

[4] Early work [e.g., *Sonnerup*, 1970] on reconnection suggested that it should occur along an XL in the surface separating two regions of differing magnetic field (strength and direction), the field lines of which were taken to approach the boundary surface tangentially. The orientation of the XL on the separating surface was then thought to be determined by the requirement that the two fields must have equal components parallel to the XL. The rate of reconnection would then be proportional to the orthogonal (reconnecting) components and would fall to zero when the angle between the reconnecting fields falls below a minimum angle [*Gonzales and Mozer*, 1974; *Hill*, 1975]. The minimum angle vanishes for equal field magnitudes. The apparent preference of reconnection for regions of large field shear was pursued to its conclusion by *Crooker et al.* [1979] and more quantitatively by *Luhmann et al.* [1984]. Both argued that reconnection would occur principally in regions of nearly antiparallel magnetic fields, which regions could be identified on the magnetopause by superposing a typical magnetosheath field upon the typical magnetospheric internal field near the magnetopause.

[5] However, *Cowley* [1976] showed that no such requirement is placed upon reconnection by the MHD equations, opening up a wider range of possible reconnection between fields with relatively little shear separating them. In Cowley's formulation, the orientation of the XL is instead normal to a line along which the two fields have equal and opposite components, to which we refer as the "reconnecting component," to distinguish it from the component parallel to the XL, also referred to as the "guide field." *Cowley and Owen* [1989] further developed this theme, showing how subsolar component reconnection concepts can be used to compute flux tube and boundary layer motions all across the magnetopause, with realistic results. This approach was also rationalized on an energetic basis by showing that component reconnection at the right location would result in the loss of field energy to the plasma on both sides of the XL, i.e., that reconnection would produce $\mathbf{J} \cdot \mathbf{E} > 0$ in the vicinity of the XL. There is then no lower limit on the shear that is required for reconnection, though the limiting rate goes to zero with the reconnecting component, plasma density being otherwise constant.

[6] Observations supporting the occurrence of low shear or component reconnection (terms we shall use interchangeably) have been published by, among others, *Gosling et al.* [1990] and *Onsager and Fuselier* [1994]. At the same time, it has become clear [*Kessell et al.*, 1996; *Russell et al.*, 1998; J. D. Scudder et al., unpublished manuscript, 2001] that reconnection is common at high latitudes above the cusps, where northward interplanetary magnetic field (IMF) should indeed lead to antiparallel reconnection regions. However, in a recent study [*Chandler et al.*, 1999], it was found that the midlatitude magnetosheath plasma contained substantial amounts of ionospheric plasma at a time when reconnection was known to be occurring poleward of the cusp essentially simultaneously. This gave rise to the conclusion that low shear component reconnection must be occurring in the subsolar region at the same time as high shear reconnection, poleward of the cusps. Another relevant recent observation comes from the IMAGE mission, where the innovation of proton auroral imaging has yielded observations suggesting a complex distribution of reconnection on the dayside, including both high- and low-latitude extensions from the nominal auroral oval [*Fuselier et al.*, 2001].

[7] In this paper, we explore an alternative to the antiparallel reconnection hypothesis for the dayside magnetosphere. We propose that a continuous XL must join the steady state sites of reconnection on the magnetopause, lying everywhere tangent to the local XL direction within each reconnecting region. This amounts to proposing that reconnection extends away from any site where it begins along an integrable XL that is everywhere tangent to the local XL direction, at a limiting rate that varies from point to point along the XL according to the local magnitudes and orientations of the reconnecting fields. As pointed out by *Nishida* [1989], reconnection is constrained, at least in quasi-steady state, to be topologically smooth so that neighboring field lines do not become entangled. We suggest, but do not show rigorously, that reconnection occurring along the integrable XL we compute here satisfies the quasi-steady requirement that reconnection should not create more complex fields. We do, however, assert a limited form of the antiparallel reconnection hypothesis and take the XL to extend away from the magnetopause site with maximal reconnecting component. Essentially, we argue that this site serves as an origination point or anchor for reconnection.

[8] We then follow the analysis of *Cowley and Owen* [1989], accepting the general assumptions laid out there, but relaxing the requirement of a straight XL. Integrating the local XL direction to obtain the XL, we pursue the consequences of component reconnection for the shape and limiting rate of dayside reconnection over the magnetopause, and for the motions of the boundary layer plasma just inside the magnetopause, in response to reconnection. In the following sections, we detail our calculation approach, exhibit the results of the calculations, then discuss their implications, and summarize with conclusions.

2. Calculation Technique

[9] The first step of this calculation is to specify a realistic configuration of the dayside magnetopause region magnetic field, interior to the magnetopause, and independent of any interplanetary magnetic field. We elected to do this using the *Tsyganenko and Stern* [1996] magnetic field model. This model is based largely on the statistical analysis of numerous magnetic field observation databases. It includes realistic magnetopause currents and field-aligned currents, though these are not used for our purposes. The T96 field just inside the magnetopause is significantly distorted from the expected compressed dipole field owing to magnetopause currents. In order to eliminate perturbations owing to the presence of the magnetopause, we evaluated the magnetic field on a surface lying 0.5 Earth radius interior to the magnetopause, along the local normal to the magnetopause itself. We evaluated the magnetic field for zero tilt, IMF magnitude of 3 nT (negative *Bz*), and a typical solar wind dynamic pressure of 2 nPa. The typicality of these choices should be apparent but are best reflected in the results to be displayed at a later point. Effectively, we assumed that the field components given by T96 on this surface represent the

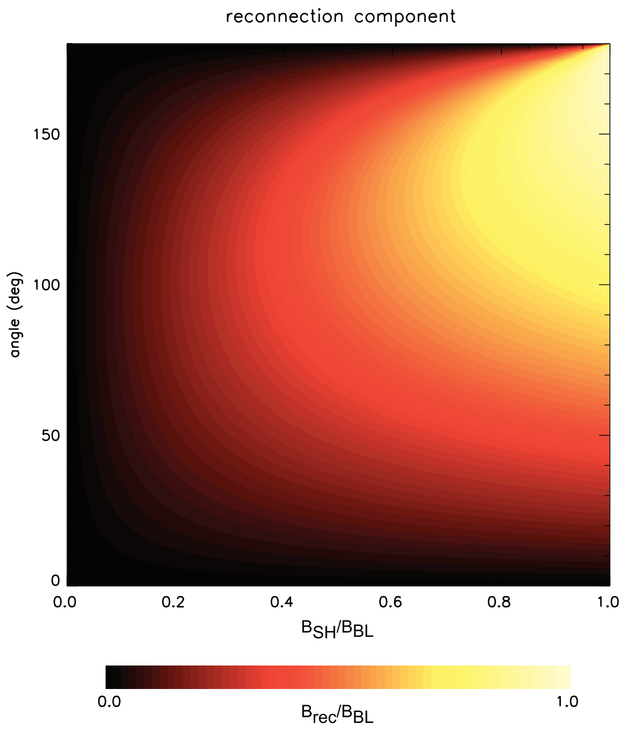

Figure 1. Reconnecting component for sheath and boundary layer fields as a function of their relative angle and of their relative magnitudes.

internal magnetospheric field presented to the magnetosheath for reconnection, effectively setting up a virtual magnetopause 0.5 R_E inside the T96 magnetopause.

[10] The second step was to represent the interplanetary magnetic field as deformed by draping within the magnetosheath. The goal is to represent the magnetosheath field that would obtain at the magnetopause if the magnetopause were a nonreconnecting surface. On the basis of inspection of the magnetopause field in several MHD simulations available for public viewing on the Web site of the Coordinated Community Modeling Center (http://ccmc.gsfc.nasa.gov), we used the following approach. The magnetosheath field, when projected into the GSM *Y-Z* plane is assumed to lie everywhere parallel to the interplanetary field clock angle direction, i.e., arctan(By/Bz) (0 to 2π). Draping is assumed to create a Bx component just sufficient to cause the magnetosheath field at the magnetopause to lie everywhere tangent to the local magnetopause surface, as given by a surface 0.5 R_E inside the T96 magnetopause, along local normals.

[11] The third step was to compute the reconnecting component of the magnetic fields and the orientation of the reconnection XL at each point on the magnetopause. This involves the determination of the XL direction, and computation of any components of the magnetic fields lying parallel to the XL so as to find the reconnecting component. Initially we had planned to allow the reconnecting fields (interior and exterior to the magnetopause) to have independent magnitudes as well as directions. The IMF magnitude would then be a variable of the problem, in addition to its orientation. The following relations for the reconnecting component and the XL orientation were used. These were derived from the definition of the XL direction as that direction normal to which the two reconnecting fields have equal and opposite components [*Cowley*, 1976]:

$$(dZ/dY)_{\mathrm{XL}} = m, \tag{1}$$

where m is the slope dZ/dY of $\mathbf{B}_{\mathrm{SH}} + \mathbf{B}_{\mathrm{BL}}$,

$$\mathrm{B}_{\mathrm{rec}} = |\mathbf{B}_{\mathrm{BL}} \cdot \mathbf{i}_{\mathrm{XN}}|, \tag{2}$$

and $\mathbf{B}_{\mathrm{SH}}$ is the magnetic field in the magnetosheath, $\mathbf{B}_{\mathrm{BL}}$ is the magnetic field inside the magnetopause, and $\mathbf{i}_{\mathrm{XN}}$ is the unit vector normal to the X line, i.e., whose slope is $-1/m$.

[12] Figure 1 illustrates these relationships as a color contoured plot of $B_{\mathrm{rec}}/\mathrm{B}_{\mathrm{BL}}$ as a function of both the ratio of the reconnecting magnetic fields ($\mathrm{B}_{\mathrm{SH}}/\mathrm{B}_{\mathrm{BL}}$), and the clock angle between them. Looking first at the variation of $\mathrm{B}_{\mathrm{rec}}/\mathbf{B}_{\mathrm{BL}}$ with fixed $\mathbf{B}_{\mathrm{SH}}/\mathbf{B}_{\mathrm{BL}} = 1$, we see as expected that the reconnecting component goes from small values at small clock angles (near parallel) to unity for clock angles approaching 180°. This represents a continuous increase in the limiting rate of reconnection, or for given plasma density, the reconnection Alfvén speed, with increasingly antiparallel fields. The essence of component reconnection is that its limiting rate only approaches zero as the fields become parallel and is otherwise finite.

[13] However, for $\mathbf{B}_{\mathrm{SH}}/\mathbf{B}_{\mathrm{BL}} < 1$, we find behavior that is somewhat surprising, with peak reconnecting component for intermediate values of the clock angle, and decreasing reconnecting component for antiparallel fields. This is readily seen in Figure 1, but not so readily visualized without resort to corresponding diagrams of the reconnecting fields for different magnitudes. We found this behavior somewhat troubling and wondered if this revealed some problem with our assumptions.

[14] Referring to *Cowley and Owen* [1989], we realized that we were making an error in our assumption of independent magnetosheath and magnetospheric field magnitudes. If reconnecting fields create a rotational discontinuity on the magnetopause, through which plasma passes freely, it is then clear that to first order the magnetosheath and boundary layer fields must have equal magnitudes. The plasma pressure balance boundary then exists somewhat interior to the magnetopause, at the boundary of opened and closed field lines, from which the in-streaming magnetosheath plasma is excluded. With this additional assumption, we are then dealing with the special case of Figure 1 in which $\mathbf{B}_{\mathrm{SH}}/\mathbf{B}_{\mathrm{BL}} = 1$, along the right-hand Y axis. That is, we henceforth assume that $|\mathbf{B}_{\mathrm{SH}}| = |\mathbf{B}_{\mathrm{BL}}|$.

[15] We then check our field models by attempting to reproduce the results of *Luhmann et al.* [1984]. This is done by evaluating the sheath and boundary layer fields at the virtual magnetopause defined above (0.5 R_E interior to the T96 magnetopause), and computing the cosine of the angle between them. Figure 2 shows the results as contour plots of cos(A), where A is the angle between the two fields, for varying IMF clock angle. Regions of nearly antiparallel fields are indicated by the contours in a manner similar to that used by *Luhmann et al.* [1984], with red shading for the regions of most negative cos(A), or most antiparallel fields. Comparison with Figure 2 of *Luhmann et al.* [1984], shows that our results are qualitatively very similar, demonstrating the essential similarity of our magnetospheric and sheath

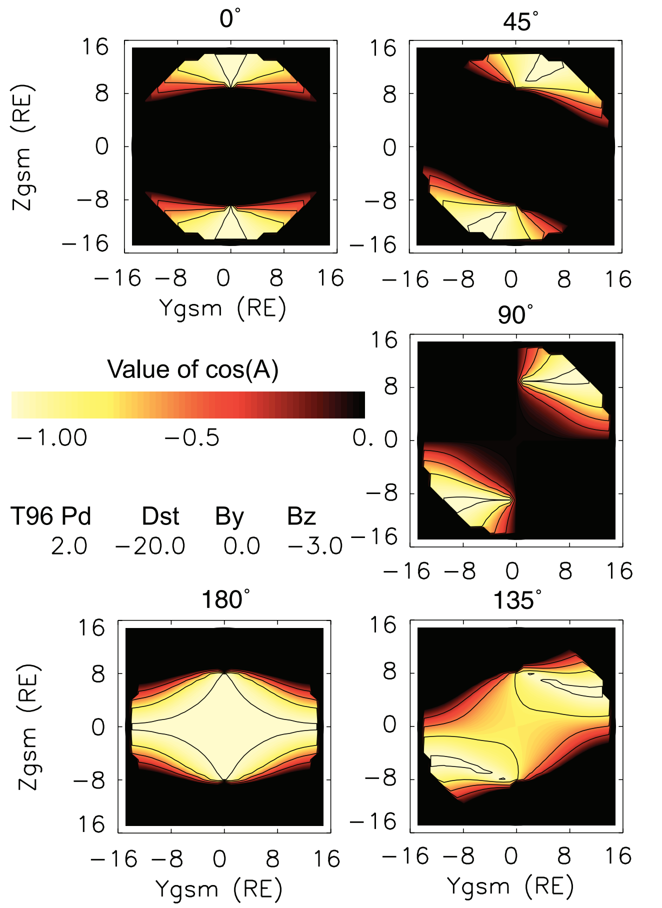

Figure 2. Contour plots of the value of cos(A) over the dayside magnetopause, as projected on a plane normal to the viewing direction from the Sun. A is the angle between the sheath magnetic field and the magnetospheric boundary layer field, at the virtual magnetopause defined in the text (0.5 R_E inside the T96 magnetopause). Individual plots represent the results for various interplanetary magnetic field clock angles according to their labels. The T96 parameters used are indicated.

field models. The familiar features of the regions of antiparallel fields, also pointed out by *Crooker* [1979], are readily apparent. These are the following: (1) the emanation of regions of antiparallel fields away from the cusps toward the flanks, at an angle that follows the clock angle of the IMF, (2) the failure to obtain antiparallel fields in the subsolar region except at perfectly southward IMF, and (3) the confining of antiparallel conditions to the region directly poleward of the cusps for perfectly northward IMF.

[16] The next step of our calculation was to choose the point with maximal reconnecting component and to integrate the local XL away from the that point, tracing it wherever it leads, just as one would trace the streamlines of any vector field. For simplicity, tilt effects were not considered. The calculation is relatively straightforward, but does require care in one particular aspect. When an XL direction is locally integrated along a sequence of points on the magnetopause, it will intersect at a large angle the antiparallel locus (the hypothetical antiparallel merging locus identified in Figure 2). The XL direction is for our assumptions the bisector of the angle between the local fields. That is, the XL direction is given by the vector sum of the two reconnecting fields. Thus the direction of the XL vector will reverse in direction across the locus of antiparallel fields, passing through zero in magnitude. If this is not treated with care, it will interrupt or cause errors in the integration of the XL beyond this crossing point.

[17] The final step is to compute the direction of the de Hoffman-Teller (HT) flow (motion of reconnecting field lines at the magnetopause), and the boundary layer (BL) flow, inside the magnetopause. This is done according to the method of *Cowley and Owen* [1989], as schematically illustrated in Figure 3. The plasma is assumed to flow in a given radial expansion away from the subsolar point at $\mathbf{V}_{SH}$ and along the magnetopause. The sheath (SH) flow is characterized by a single parameter, R_A, the radius from the subsolar point at which the flow reaches Alfvénic velocity tangential to the magnetopause (16 R_E here). An HT frame is defined as the frame in which the plasma flows at the Alfvén speed along both the SH and BL fields and has zero velocity perpendicular to the local magnetic field. This frame is constructed by shifting the local SH flow by the flow at V_A parallel to $\mathbf{B}_{SH}$. The BL flow $\mathbf{V}_{BL}$ is constructed by noting the sum of the $\mathbf{V}_{HT}$ and $\mathbf{V}_{BL}$ as seen from the HT frame, as shown in Figure 2. The result is a specification of both the HT and the BL flow, at selected points on the magnetopause and near the XL. Following the example of *Cowley and Owen* [1989], we have computed velocities as normalized to the Alfvén speed, since absolute velocities and rates are not the main objects of this investigation.

3. Results

[18] Our main results are summarized in Figure 4, in which plots from selected clock angles of IMF are arranged in an analogous (half) clock-like display. In the following description, we begin with the *SBz* case, and then proceed around in the direction of *NBz*. The assumed fields are symmetric so that it makes little difference in which

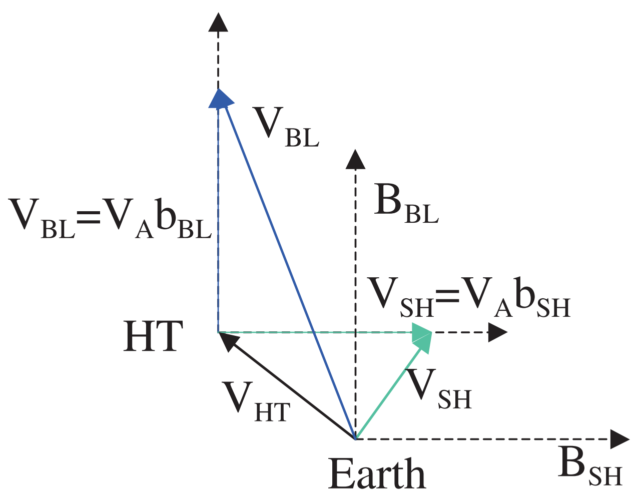

Figure 3. Graphical representation of the calculation of *Cowley and Owen* [1989], for the de Hoffman-Teller frame and the boundary layer frame, given the magnetosheath flow and magnetic fields.

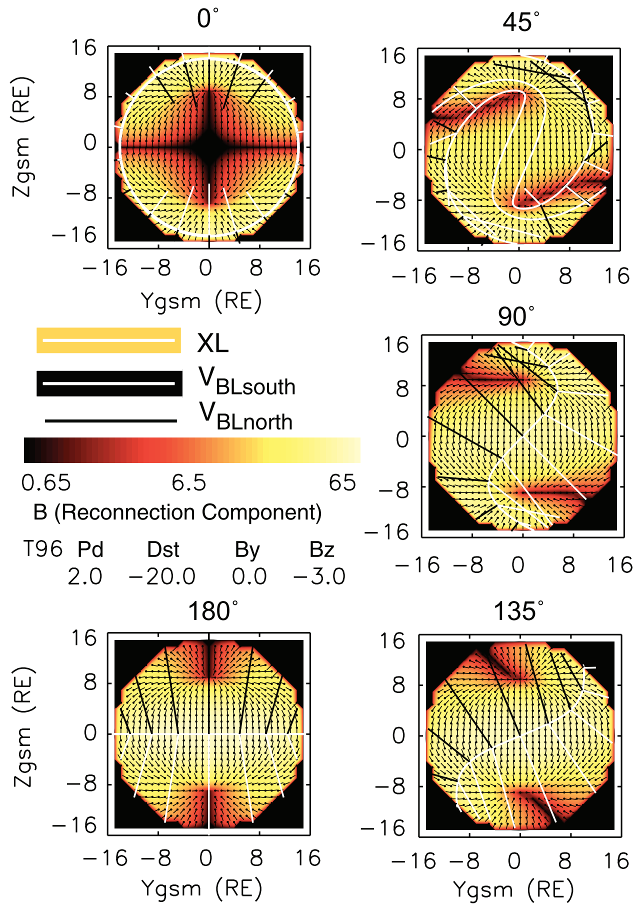

Figure 4. The configuration of magnetic field just inside the virtual magnetopause (small black arrows), the reconnecting component magnitude (color scale), and resultant X line (XL) when integrated away from the point of maximal reconnecting component. Boundary layer flow (white and black vectors) for field lines rooted in each hemisphere, on each side of the XL, as projected on the plane normal to a view from the Sun. Individual plots represent the results for various interplanetary magnetic field clock angles according to their labels.

direction this proceeds, and we have chosen to go through positive *By*.

[19] We consider first the *SBz* case at bottom center of Figure 4 (clock angle is 180°). Color contouring is used to indicate the magnitude of the reconnecting component, as defined in the introduction, and with reference to a magnetosheath field assumed to be oriented due southward and to be equal in magnitude to the local field inside the magnetopause. All of this is with respect to the virtual magnetopause at 0.5 R_E inside the T96 magnetopause, as defined above. The field intensity scale is logarithmic, spanning 2 decades. The black channels poleward of the cusps indicate where the fields are essentially parallel, resulting in a very small reconnection component. The local field orientation inside the magnetopause is indicated by the small windsocks, which point away from the southern cusp, generally toward the N pole across the equatorial region, and then toward the northern cusp. The white horizontal line is the integrated XL for this geometry, showing that it cuts straight across the equator through the subsolar point, as expected for exactly southward *Bz*. In combination with the color coding along this line, this indicates the potential for strong antiparallel reconnection across the entire magnetopause, with field lines parting and then opening toward the poles. The boundary layer flow deviates away from the radial magnetosheath flow over the poles, as described by *Cowley and Owen* [1989], and shown by the red and black boundary layer flow vectors placed at intervals along the XL. This deviation of the boundary layer flow is accomplished by field stresses owing to the reconnection along the XL.

[20] We next consider the case with clock angle of 135°, in the lower right corner. Here the color distribution is similar, but the dark parallel field channels now tilt off to the sides, and there is a slight tilt of the ridge of high values of reconnection component. More significantly, the XL now integrates up toward the poles as it proceeds away from the subsolar point. Overall, this corresponds to a tilt of the HT flow pattern (not shown) off toward opposite sides of the polar caps in the opposing hemispheres. The enhanced boundary layer flow is now correspondingly tilted as well. Owing to the tilt of the XL, the largest values of reconnecting component are found along the parts of the XL closest to the subsolar point.

[21] Next we examine the case of clock angle of 90°, at the right and just above the 135° case. Here the black channels now extend laterally away from the cusps in opposite directions, while the peak reconnecting component near the equator is still more tilted, and of lower magnitude, owing to the increasing departure from antiparallel reconnection. The XL now integrates significantly up toward and around the cusps, rather than across the magnetopause. The strongest reconnecting component continues to be found along the part of the XL that is nearest the subsolar point. The boundary layer flow in this case is now directed largely toward the flanks of the magnetopause, with less and less tilt toward the poles.

[22] When we reach clock angle of 45°, the next panel up in Figure 4, we find that the distribution of reconnecting component over the magnetopause now favors the strongest reconnection at locations poleward of the cusps. The dark channels of parallel fields now tilt down toward the equator as they radiate from the cusps. An XL is now initiated in the northern supra-cusp region (where the reconnecting component is maximal). It loops equatorward around the flank, then loops around the southern cusp, returning across the subsolar region before again looping the northern cusp region and passing beyond the region of interest. The XL originating from the southern supra-cusp region takes a mirror image path, nesting within the northern cusp XL. The distribution of reconnecting component, while significantly smaller than that found near the equator for *SBz*, remains substantial along most of the XL, peaking at latitudes above both cusps, but with a secondary maximum near the subsolar region. The induced reconnection flows represent a gathering of flux tubes broken open both across the subsolar region and up over the cusps, off toward the flanks of the magnetopause, as indicated by the relevant boundary layer flow vectors. In this case, the XL has essentially bifurcated into high- and low-latitude branches, which cannot be unified into a single curve. The split occurs as the XL crosses the region of parallel fields marked by the dark

streaks. Here the reconnection rate vanishes, and it is meaningless to integrate the XL across this region. Nevertheless, we suggest that the actual result in this case will be a single separate S-shaped XL in the low-latitude region, that is a compromise between the two traces shown, which were formed by extending the high-latitude XLs through the region of zero reconnecting component. The rate at which reconnection occurs on this low-latitude branch should be determined by the magnitude of the reconnecting component at the subsolar point, and other relevant conditions. Since both subsolar and supra-cusp maxima of the reconnecting component are appreciable, and since the stagnation pressure is quite high in especially the subsolar region, it seems plausible that reconnection may be produced there as well as above the cusps.

[23] Finally, in the case where clock angle is 0°, as seen in the top left panel of Figure 4, we find that the black troughs of parallel fields join the cusps across the equator, while the XL integrates from the supra-cusp maxima of the reconnecting component, around in a closed circle. The induced flow in this case tends to close and trap flux tubes in the subsolar region, presumably leading to a pressure buildup in flux tubes there. On the basis of this result, passage of *By* through zero for *NBz* should produce the *Song and Russell* [1992] phenomenon of newly closed flux tubes containing substantial amounts of stagnated magnetosheath plasma.

4. Discussion

[24] The results presented above suggest that the orientation of the magnetosheath field is a continuum that allows a corresponding continuum of reconnection responses. It is clear that reconnecting component magnitudes are substantial where fields are antiparallel. However, it is by no means clear that reconnection can only have appreciable rates where this criterion is satisfied or nearly satisfied. Nevertheless, it must be admitted that local enhancement of reconnection in response to microphysical instabilities has not been considered here, so the reconnecting magnitude we are looking at only sets an upper limit on the reconnection rate. However, we see no clear distinction possessed by regions of antiparallel reconnection that sets them apart from the rest of the magnetopause.

[25] Component reconnection provides for a continuum of limiting reconnection rates that vanish only where the fields are actually parallel. It also provides a local definition of the XL, along which field lines are expected to break and reconnect. In this paper we have pursued the hypothesis that reconnection extends away from its most powerful site(s) along an XL defined by local conditions, to form a topological boundary along which reconnection may occur. We suggest but have not proven that the XL defined in this way also has the property of allowing continuous reconnection without creation of more complex fields, a requirement proposed by *Nishida* [1989].

[26] The main consequence of our results appears to be that the subsolar region should be actively reconnecting for virtually all southerly or Parker spiral orientations of the magnetosheath magnetic field. For northerly orientations, since a ridge of substantial reconnecting component continues to lie across the subsolar region, the complexity of the XL looping patterns we find suggests that separate subsolar and supra-cusp XLs may form, separated from each other by regions of low reconnecting component and limiting rate. The subsolar limiting rate is lower than the high-latitude limiting rate, but both rates contribute to the induction of enhanced downstreamflow in the LLBL, as contrasted with the mantle, which is enhanced only for southerly *Bz*.

[27] All limiting reconnection rates (reconnecting component magnitudes) in our calculation scale directly with the IMF, as does the degree of compression of the magnetopause. While the typical solar wind is typically of high dynamic beta, this is not as true of the disturbed solar wind, which can have increases of IMF magnitude that far exceed corresponding increases of dynamic pressure. Indeed, it has recently been found that CMEs, which are notable for their geoeffectiveness, are distinguished by a dynamic inverse beta (ratio of field to plasma pressure) that is very much elevated from typical solar wind values [*Osherovich et al.*, 1999]. It seems plausible that the internal excitation of the magnetosphere should track the convolution of the local magnitude of reconnecting component, together with other relevant microphysical effects, along the XL as defined herein or by a more extensive integration over the entire three-dimensional magnetopause. The boundary layer flows of Figure 4 appear qualitatively consistent with throat-like cusp flows toward the dawn (dusk) for positive (negative) *By*.

[28] It should be interesting and revealing to examine how well the simple assumptions and calculations presented herein agree with results from full 3-D simulations of the magnetopause region. Preliminary results from the ISM code (G. Siscoe, personal communication, 2001) suggest that our component reconnection picture is in general agreement with that simulation, at least for southerly or Parker spiral IMFs.

[29] The antiparallel reconnection hypothesis states that the locus of dayside reconnection follows the peak of the reconnecting component across the magnetopause, emanating from the cusps and avoiding the subsolar region, except in the singular case of exactly southward IMF [*Crooker et al.*, 1979; *Luhmann et al.*, 1984]. In contrast, the component reconnection hypothesis pursued here clearly places the XL directly across the subsolar region for all but northerly IMF. It is difficult to envision two more orthogonal results, especially considering that we infer that the XL must intersect the ridge of antiparallel fields at a large angle, near 90°. Clear observations of reconnection in the low latitude, subsolar region for average solar wind conditions [e.g., *Gosling et al.*, 1990] make a strong case that this result is qualitatively correct and that the reconnection XL is constrained according to component reconnection.

5. Conclusions

[30] We have shown that the concept of component reconnection provides a quantitative measure of the limiting rate of reconnection at any point on the magnetopause, as a function of interplanetary or magnetosheath magnetic field orientation. Moreover, this prescription provides a definition of the local XL orientation that can be integrated to yield a macroscopic XL traversing the dayside magnetopause, again as a function of IMF. Such an XL is proposed

to represent the steady state or average locus of reconnection on the dayside magnetopause. We derived the shape of the XL, assuming that it extends from that region or regions on the magnetopause with maximal reconnecting component (or equivalently, limiting reconnection rate). From this, we conclude the following: For southward *Bz*, the XL lies across the subsolar equatorial magnetopause, as expected. During *By*-dominated periods, simultaneous high- and low-latitude reconnection is expected along different parts of a single S-shaped XL, with comparable limiting rates in both regions. Northerly directed IMF results in complex XL behavior that suggests separate northern and southern XL traces, and a separate subsolar XL trace when the reconnecting component is sufficiently strong there. Subsolar reconnection should shut down completely only for exactly northward IMF. Exactly northward IMF results in northern and southern XL traces that meet at the flanks to form a closed loop, indicating the formation of newly closed flux tube in this singular case. The net excitation of the magnetosphere and ionosphere should track the convolution of the local limiting rate and the local microphysical conditions, integrated along the XL. Other parameters being constant, strong modulation of magnetospheric excitation by clock angle and IMF magnitude are expected from these results.

[31] **Acknowledgments.** This work was supported by the GGS/Polar Mission under UPN 370-17-43; by the NASA Office of Space Science Sun Earth Connection theme, Research and Analysis program, under UPN 344-09-14, "Plasma Transport and Energization"; and UPN 344-14-00, "Magnetic Reconnection and Particle Precipitation Across the Magnetopause". The authors are indebted to S. A. Fuselier and S. W. H. Cowley for important advice and encouragement. The authors are indebted to the referees of an earlier version of this paper for important corrections and constructive suggestions.

[32] Lou-Chuang Lee and Chin S. Lin thank Walter D. Gonzalez and another reviewer for their assistance in evaluating this paper.

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